A Five Colour Photometry and Polarimetry of the Zodiacal Light: A Preliminary Report

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Abstract

Simultaneous observations in five colours of the brightness and state of polarization of the night sky radiation were secured from Mount Chacaltaya, Bolivia, during July and August 1964. The spectral range was from 3650 to 9515Å. The results of a preliminary analysis of part of this data are presented: these include a description of the wavelength dependence of the zodiacal light brightness and polarization, possible complicating emissions from the atmosphere, and some remarks concerning circular polarization of the radiation scattered by dust.

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I. Introduction

In order to deduce the spatial distribution and physical characteristics of the dust particles in interplanetary space solely from the observed properties of the zodiacal light, it is necessary to compare these properties with those calculated for a very large number of models of the interplanetary dust cloud. The properties of the zodiacal light that have been most thoroughly studied, both from the observational and theoretical standpoint, are the distributions along the ecliptic of the surface brightness and degree of polarization. For realistic models composed of mixtures of particles of different parameters, the total number of possible models is immense.

At present, the difficulty of this problem of determining a "unique" model of the dust cloud is increased by the marked uncertainty in the observed properties of the zodiacal light. Fortunately, we have reason to expect that the precision of the observations will improve in the future as observations from above the Earth's atmosphere increase and that this will help to reduce the number of models showing partial agreement with observation. Another approach that promises to reduce the number of contending models is that in which the widest categories of observation other than those mentioned above are also

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employed. One particularly hopeful line of investigation is that of the wavelength dependence of the surface brightness, state of polarization of the zodiacal light, and other quantities derivable from the Stokes parameters. In the present paper, we report observations of this type carried out at five wavelengths in the range 0.36μ to 0.95μ.

II. The Polarimeters

The distribution over the sky of the Stokes parameters (I_o, Q_o, U_o) of the night-sky radiation was obtained using an almucantar instrument (shown in Figure 1), which consists of a brace of five parallel polarimeters (numbered 1 to 5). The effective wavelengths of the observations made with the five polarimeters are listed in Table 1.

With minor exceptions, the optical arrangement of each polarimeter was identical. The layout of the number 1 polarimeter was as follows. A retardation plate, with quarter wave retardance close to the effective wavelength of the polarimeter of 3650Å (determined principally by an interference filter of 116Å equivalent width), was rotated at 15 revs/sec in front of an HNP'B polaroid placed close to the focal plane of the f/4 objective (fused quartz) of 10 cm diameter. The light from an area of sky of 5.13° diameter isolated by the field stop in the focal plane was imaged by a Fabry lens of fused quartz onto the photocathode of an EMI 6256S photomultiplier. The interference filter was placed between the Fabry lens and the photocathode. The important features of the five relevant polarimeters are summarized in Table 1.

The relation between the Stokes parameters (I_o, Q_o, U_o, V_o) of the night-sky radiation and the time dependence of the output voltage, E(t), from the photomultiplier is [see Sekera (1956)]:

$$E(t) = K\left\{I_o + \left(\frac{1-\eta}{2}\right) Q_o + \left(\frac{1+\eta}{2}\right) (Q_o^{\,2} + U_o^{\,2})^{1/2} \cos (4\omega t - 2\phi) + V_o \sin 2\omega t\right\} \quad (\omega = 15 \text{ rps}) \tag{1}$$

The retardance of the rotating quarter wave plate, $90^\circ + \eta^\circ$ was in all cases close to 90° so that $\sin \eta \cong \eta$. The Stokes parameters appearing in equation (1) are defined with respect to the instrumental system. K is a brightness calibration constant and ϕ is the angle between the polarization plane of the incident light and the transmission axis of the polaroid.

Other useful quantities can be calculated from the Stokes parameters such as the degree of linear polarization and the orientation of the observed plane of polarization; these are, respectively,

$$p_o = \frac{(Q_o^2 + U_o^2)^{1/2}}{I_o} \qquad (2)$$

and

$$\chi_o = \frac{1}{2} \arctan (U_o/Q_o) \qquad (3)$$

A useful description of the Stokes parameters and related quantities has been given by van de Hulst (1957).

III. The Observations

The observations were made from a subsidiary peak of Mount Chacaltaya, Bolivia, at an altitude of 17,630 ft. on seven nights during July and August 1964; the advantages of this site for zodiacal light photometry have been described by Blackwell and Ingham (1961).

In this paper we describe the results obtained from a preliminary analysis of the data acquired on one scan taken on August 2, 1964, with the azimuth scanner which carried the polarimeters numbered 1 to 5; the altitude of the scan was 10°. The scan was completed in 2 minutes. At the time of the observations, the solar zenith distance was $118^\circ 57'$ and the inclination of the ecliptic to the horizon was $85^\circ 3'$.

IV. Reduction of the Observations

A. The Night Sky Radiation

A brief description is given below of the method used to convert the amplified photomultiplier signals from the polarimeter into the Stokes parameters of the incident light. A more detailed description will be published elsewhere.

Phase sensitive detection of the signal provided five quantities: the mean DC level and the amplitude and phase of the components in the signal voltage that varied at frequencies of 2ω and 4ω. These five quantities could be related to the Stokes parameters of the observed radiation expressed in arbitrary units apart from a polarization calibration constant k: k was determined by making observations of a diffuse source radiating light of known $({}^{Q}/I, {}^{U}/I)$, which comprised a diffuse light source incorporating a tilting place calibrator.

In order to express the data from photometer 1 through 5 in units of the standard magnitude systems U, B, V, R, I respectively, of Johnson and Mitchell (1962), the values of the deflection, D, of bright identified stars of known magnitude and color were used to solve for the optical depth τ and calibration constants (b,c) appearing in calibration equations of the following form:

$$0.4\ U = -0.434\ \tau_1 m(z) + c_1 - 0.4b_1(U-B) - \log_{10}D_1$$

$$0.4\ B = -0.434\ \tau_2 m(z) + c_2 - 0.4b_2(U-B) - \log_{10}D_2 \qquad (4)$$

The suffices 1 and 2 refer to the data obtained with photometers 1 and 2 respectively: m(z) is the air mass at zenith distance z. From the values of D at some point in the sky measured by photometers 1 and 2, equation (4) was used to derive (U,B) for the night-sky radiation: (I_o, Q_o, U_o) could then be found from (U, B, k) in units of the equivalent number of stars of magnitude U (or B) = 10.0 per square degree. Note that the procedure described leads to two separate reductions for the B, V, and R photometers, a fact which provides a useful check on the quality of the results.

B. The Zodiacal Light

In figures 4-7 below, observational results are presented in their "observed" form, i.e., without any attempt to separate the various contaminants from the desired zodiacal light. However, in figures 2 and 3 we present intensities of the zodiacal light alone, and we describe here the procedure used in the separation.

The integrated starlight was computed for reasonable assumptions concerning the color of this radiation from the tables of Roach and Megill (1961), but only for galactic latitudes $b^I \geq 30^o$; hence, the Milky Way is still visible in the scan as a region rising above the relatively small integrated starlight correction which is applicable to the region of the zodiacal light. The mean estimate of the light scattered in the atmosphere was based on the calculations of Ashburn (1954), Fesenkov (1963), and Wolstencroft and van Breda (1967).

The airglow was removed by utilizing the rocket observations of Wolstencroft and Rose (1967 a,b). The intersections of the Chacaltaya and rocket scans allowed a determination of the airglow correction at typically 6 or 7 points in B and R. Since the rocket observations were made in B and R, only those regions where the rocket observations showed the color of the zodiacal light to be approximately the same as the Sun could be used to determine the airglow correction in U, V and I: typically there were 2 or 3 such points on each scan. The airglow correction was reasonably constant and a mean correction was applied to the scans.

The total contribution of the contaminants in figures 2 and 3 amount to 63% and 32% respectively of the maximum brightness of the zodiacal light; the use of observations from above the atmosphere has doubtless increased the accuracy of these corrections.

V. Observational Results

A. Anomalous Twilight Brightness

Removal of radiation of atmospheric origin can be a serious problem at small solar elongations. Usually, such emissions arise by fluorescence, but the enhanced radiation found in the spectral ranges λλ6800-7400Å and 9100-10,000Å exhibits a somewhat different character (Wolstencroft, Brandt, and Rose 1966); the most likely candidates for the two wavelength regions are, respectively, emission from the (8,3) and (8,4) bands of OH.

The post-twilight enhancement found is about a factor of 6 or greater and the elimination of this radiation is clearly necessary to zodiacal light studies at these wavelengths for small solar elongations; spectral identification and a judicious choice of filters may allow its removal. The atmospheric origin is probably photochemical (since fluorescence of solar radiation in the Meinel bands is thought to be negligible) as noted by Chamberlain (1961); his remarks were made in connection with the report by Sholokhova and Frish (1955) of twilight emission near 1μ.

B. Possible Circular Polarization

A rough inspection of the data indicates that some sky areas have a degree of ellipticity V/I for the combined radiation of about 0.02 which at present is strictly only an upper limit; taking account of the dilution could raise this figure to about 0.04. If this value stands up through the detailed analysis, it will require explanation in terms of scattering from specific types of optically asymmetric dust particles (van de Hulst 1957): see the discussion in the preceding paper by Wolstencroft and Rose (1967b).

C. Brightness and Polarization of the Zodiacal Light

The surface brightness of the zodiacal light (with contaminants removed as described above) in B and V is shown in figures 2 and 3; figures 4-7 show selected Q_o, U_o, p_o, and χ_o for the B and R photometers. We note again that the observations refer to an almucantar scan taken at an altitude of 10^o.

The results for the zodiacal light at $\epsilon = 39^o$ and $\beta = 0^o$ are summarized in Table 2; the uncertainties in the degree of polarization result primarily from lack of knowledge concerning the degree of polarization of the scattered light. For comparison, Smith, Roach and Owen (1965) find $S_{10}(V) = 1265$, and Weinberg (1964) gives p(5300Å) = 16.9% for the same ecliptic position; the agreement is entirely satisfactory.

The color inferred from these brightness observations is close to the value currently accepted for the Sun (see Table 3). If a blackbody extrapolation is assumed at the solar temperature, we would expect little conspicuous zodiacal light relative to the background in U and I at $\epsilon = 39^{\circ}$; this is observed. The observations made at smaller solar elongations show an identifiable contribution from the zodiacal light at these wavelengths.

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TABLE 1

Characteristics of the Individual Polarimeters

Polarimeter Number	Effective Wavelength λ_{EFF}Å	$1/\lambda_{EFF}$	Whole Half-Width of Interference Filter in Å	Angular Diameter of Field (Degrees)	Type of Photomultiplier	Type of Polaroid
1	3650	2.740	116	5.13	EMI 6256S	HNP'B
2	4510	2.217	166	5.05	EMI 9502B	HN22
3	5303	1.885	128	5.14	EMI 9502B	HN32
4	7073	1.414	316	5.20	EMI 9558B	HN22
5	9515	1.051	404	[5.13]	RCA 7102	HR

Table 2

Zodiacal light at $\epsilon = 39^{\circ}$, $\beta = 0^{\circ}$

Color	Surface Brightness, S_{10}	Degree of Polarization, P
B	770	21.9 ± 2.8%
V	1320	18.3 ± 1.8%
R	2110	20.5 ± 1.3%

Table 3

Color	ZL ($\epsilon = 39^{\circ}$)	Sun
(B-V)	0.59	0.62
(V-R)	0.50	0.53

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FIGURE CAPTIONS

Figure 1 - The almucantar instrument described in the text mounted at the observing site on Mt. Chacaltaya.

Figure 2 - The observed brightness (S_{10}) of the zodiacal light in B as deduced by the method described in the text. The data is unsmoothed. The rest position of the photometer is at azimuth 240° (measured west from south) and suppression of the data near the starting and stopping point results in the gap visible at this position in figures 2-7. The range of azimuth covered is 335°.

Figure 3 - The observed, unsmoothed brightness (S_{10}) of the zodiacal light in V as deduced by the method described in the text.

Figure 4 - A sample of unsmoothed Q_o, given here for the B observations.

Figure 5 - A sample of unsmoothed U_o, given here for the B observations.

Figure 6 - A sample of the smoothed, observed degree of polarzation (p_o) for the R photometer (determined from

smoothed values of I_o, Q_o, U_o) clearly showing the peak in p_o at the position of the zodiacal light.

Figure 7 - The change (unsmoothed) of the orientation of the observed plane of polarization, χ_o, with azimuth for the B photometer; the linear variation expected for the plane of polarization of the zodiacal light is clearly shown between 60 to 120° azimuth.

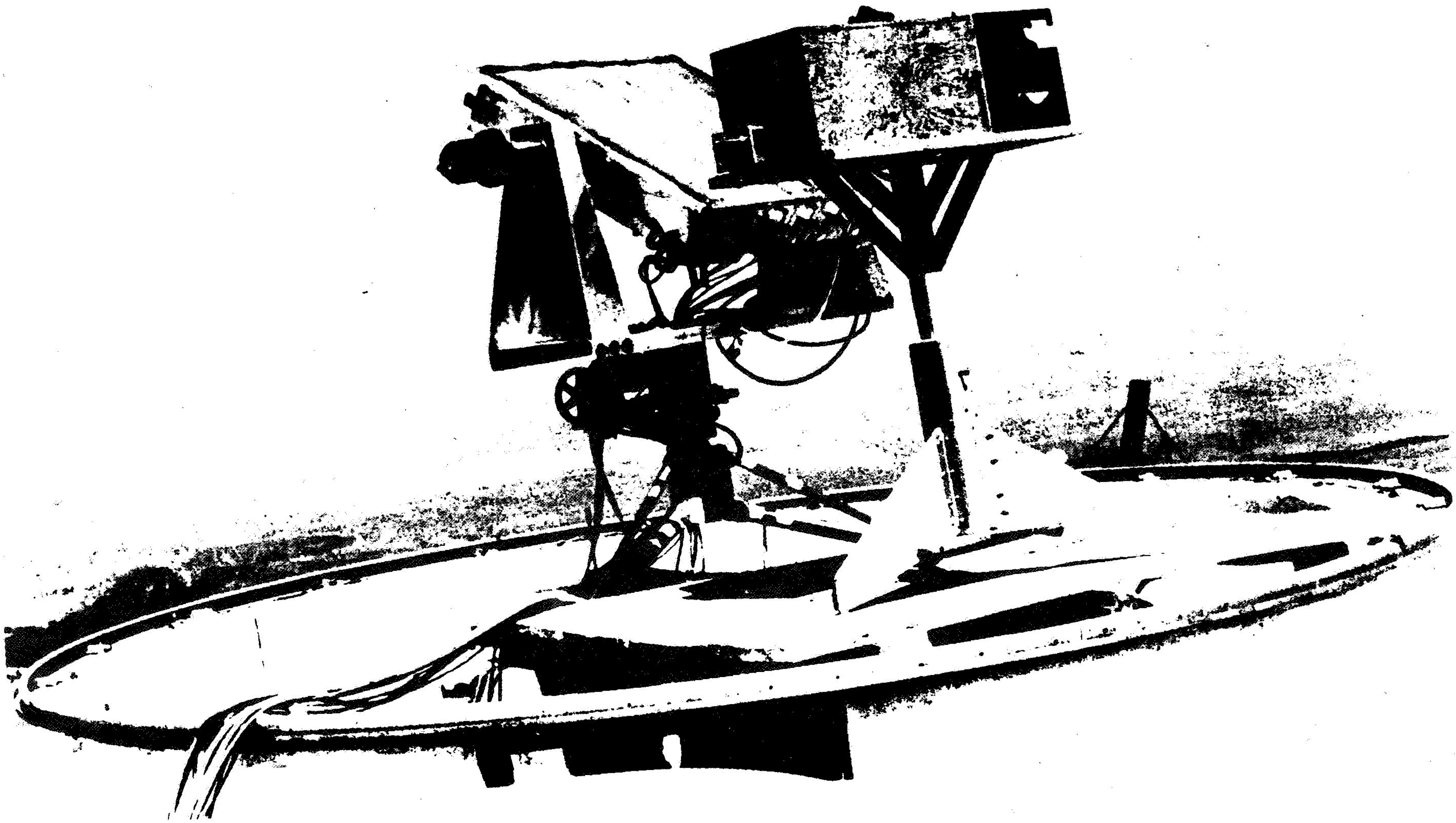


Fig. 1

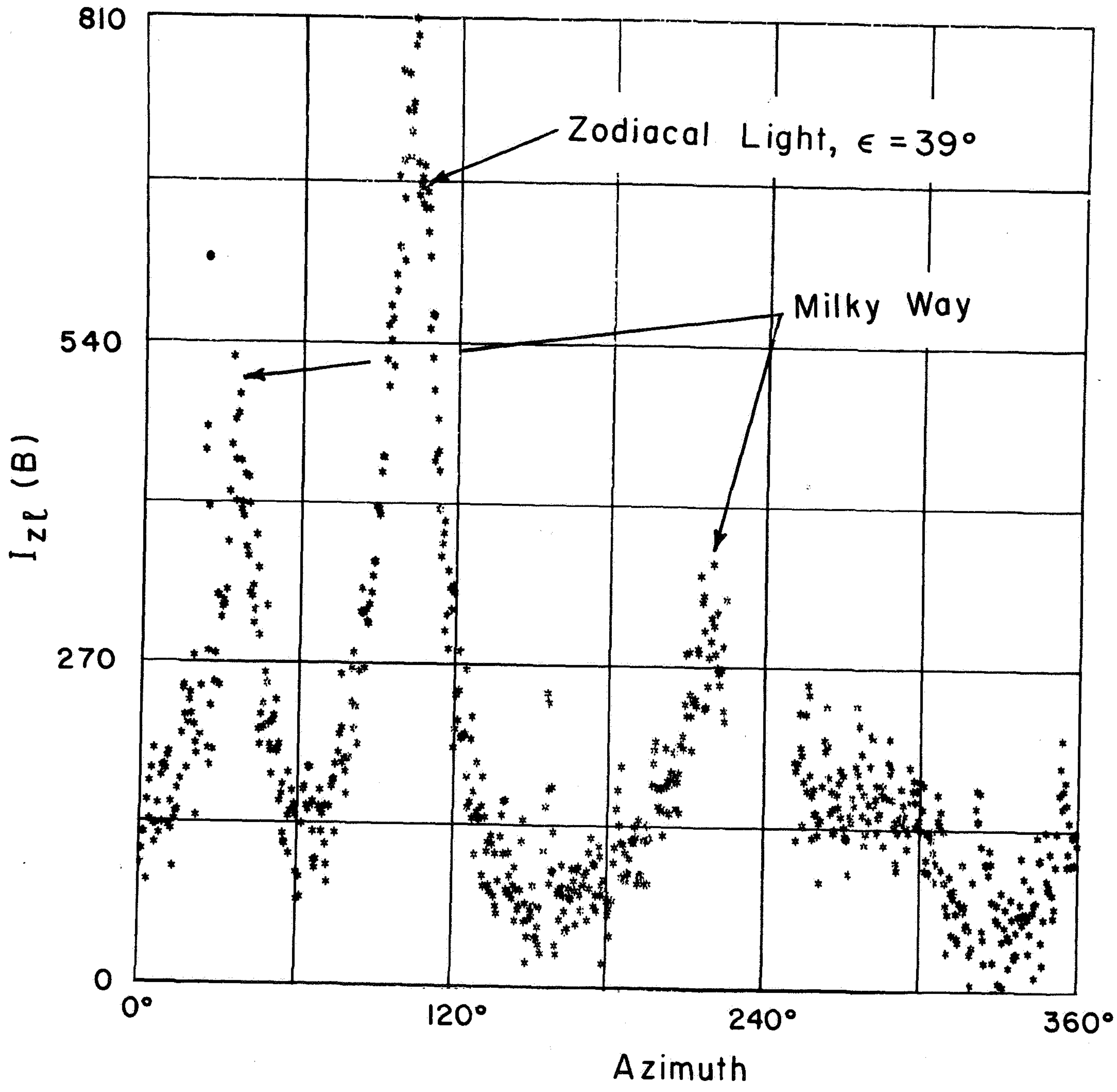

810
540
270
0
I_zl (B)
Zodiacal Light, ε = 39°
Milky Way
0°
120°
240°
360°
Azimuth

Fig. 2

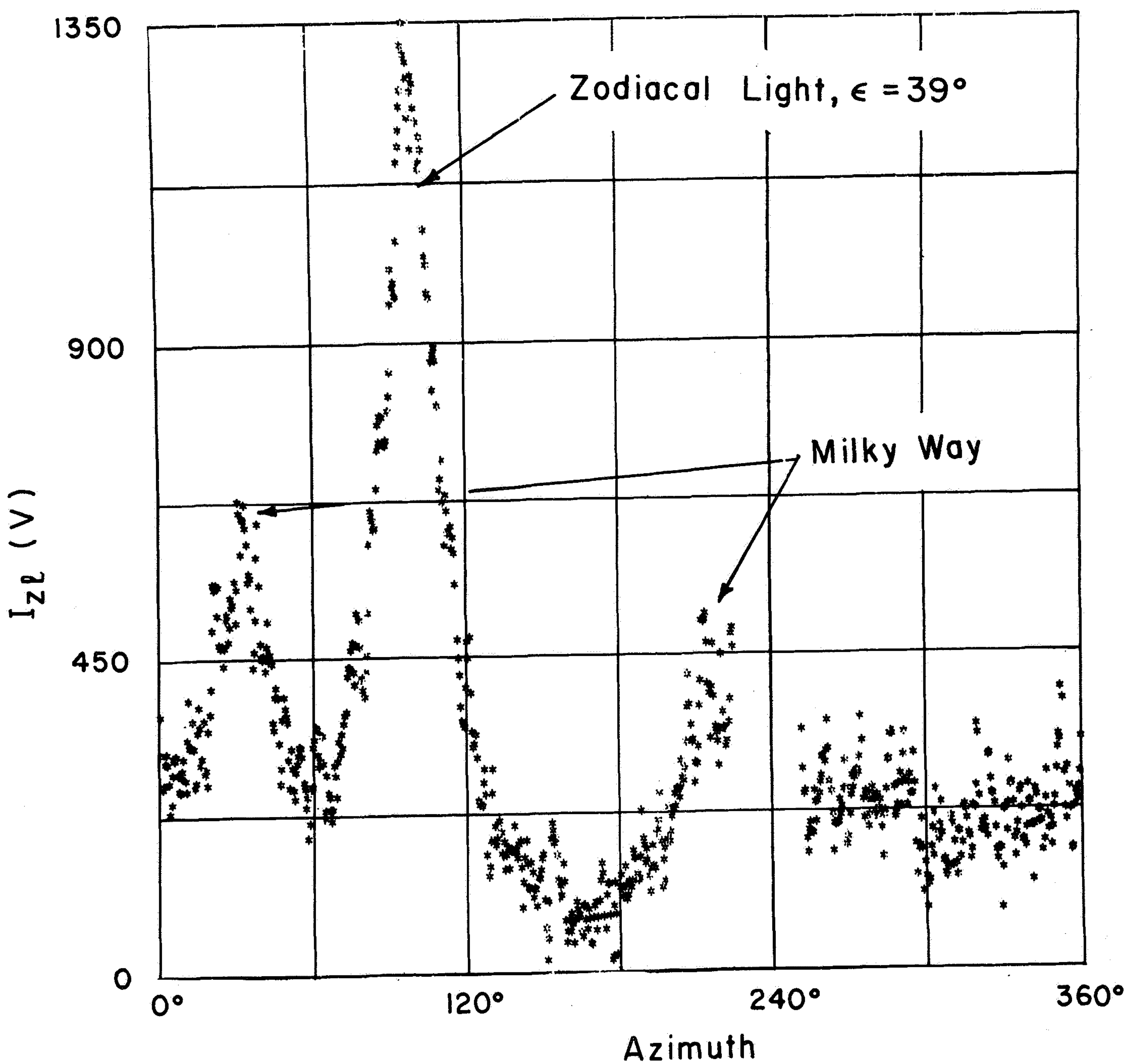

1350
900
450
0
$I_{z\ell}$ (V)
Zodiacal Light, ϵ = 39°
Milky Way
0°
120°
240°
360°
Azimuth

Fig. 3

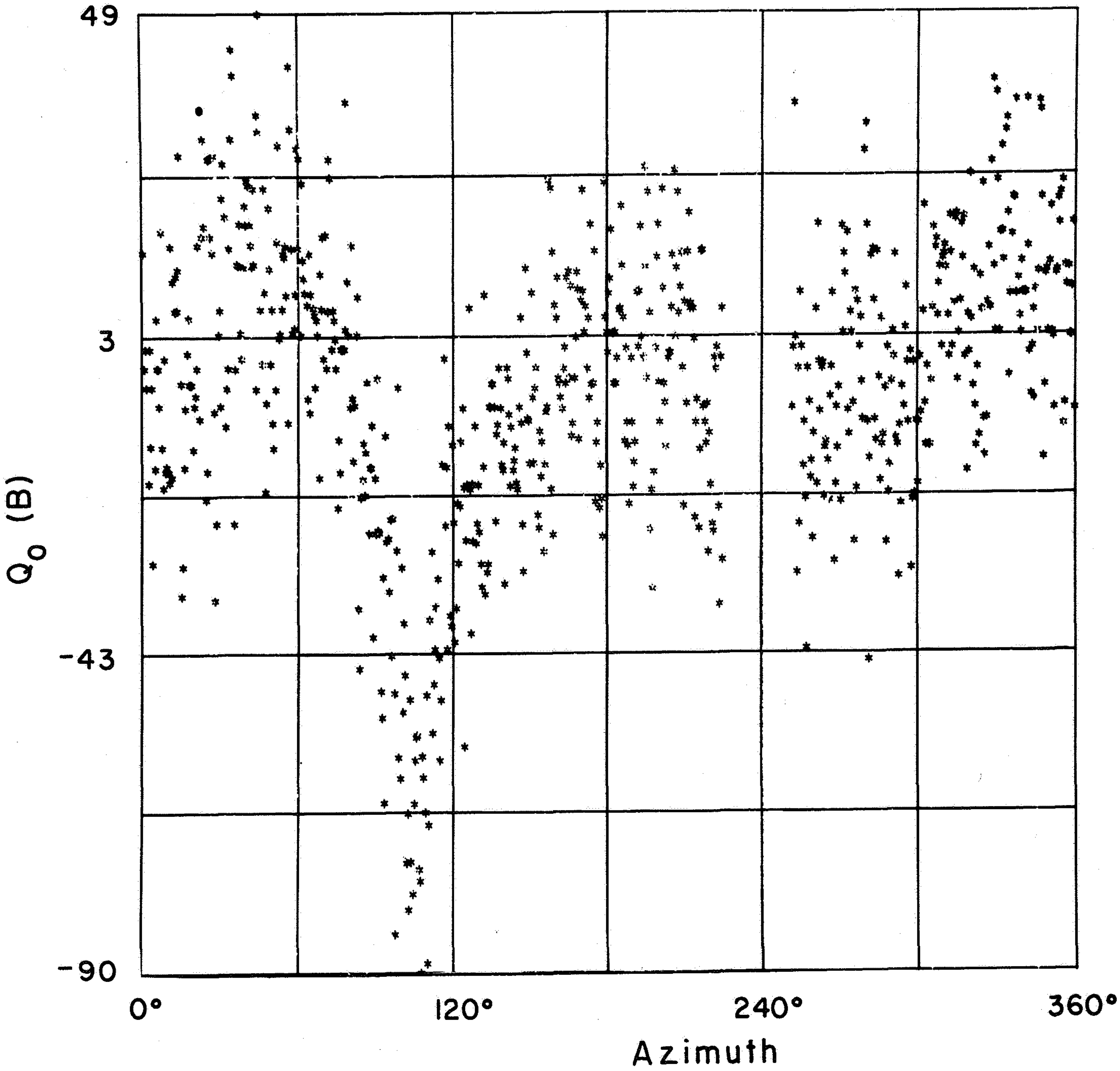


Fig. 4

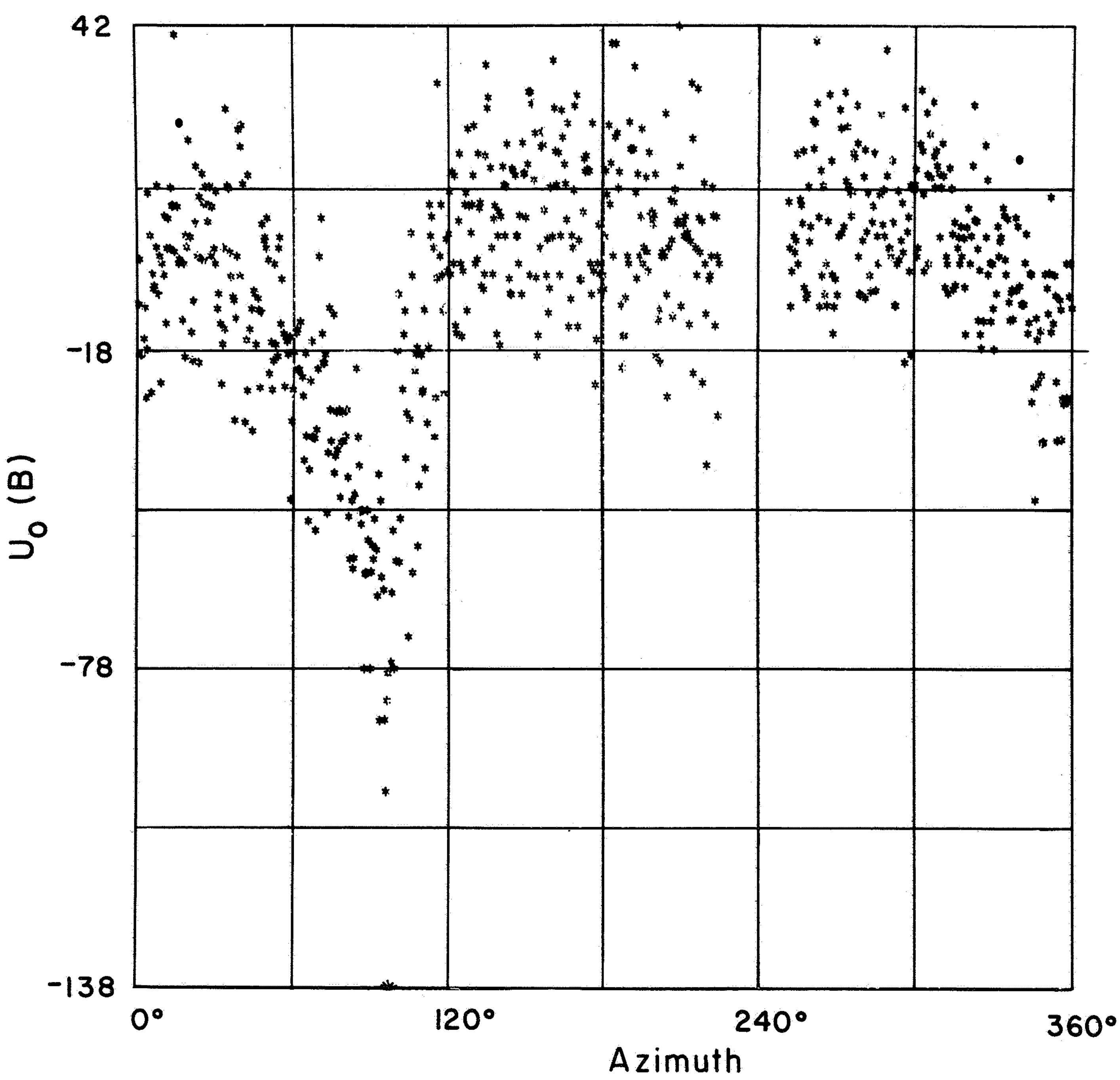
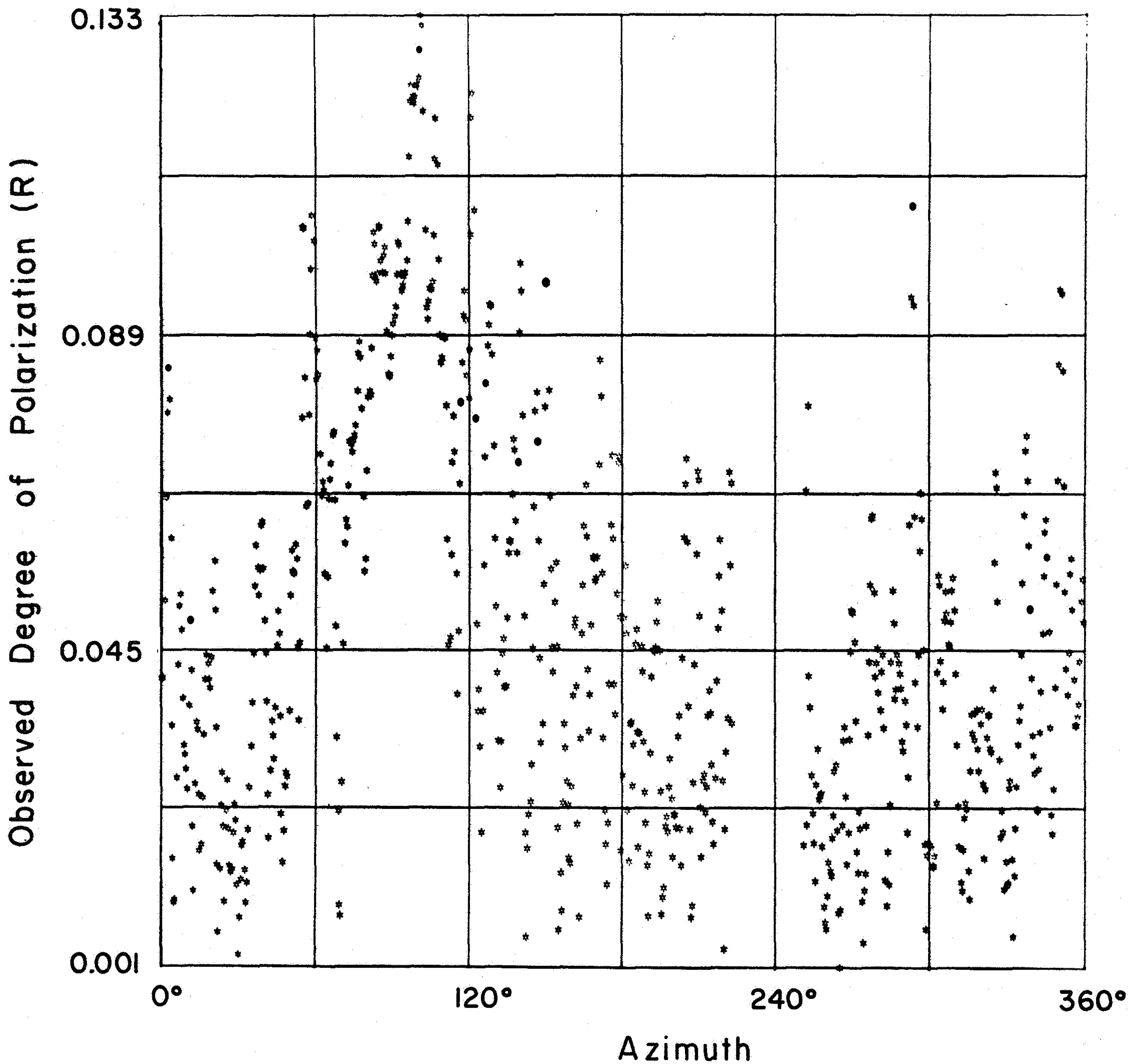


Fig. 5



0.133
0.089
0.045
0.001
Observed Degree of Polarization (R)
0°
120°
240°
360°
Azimuth

Fig. 6

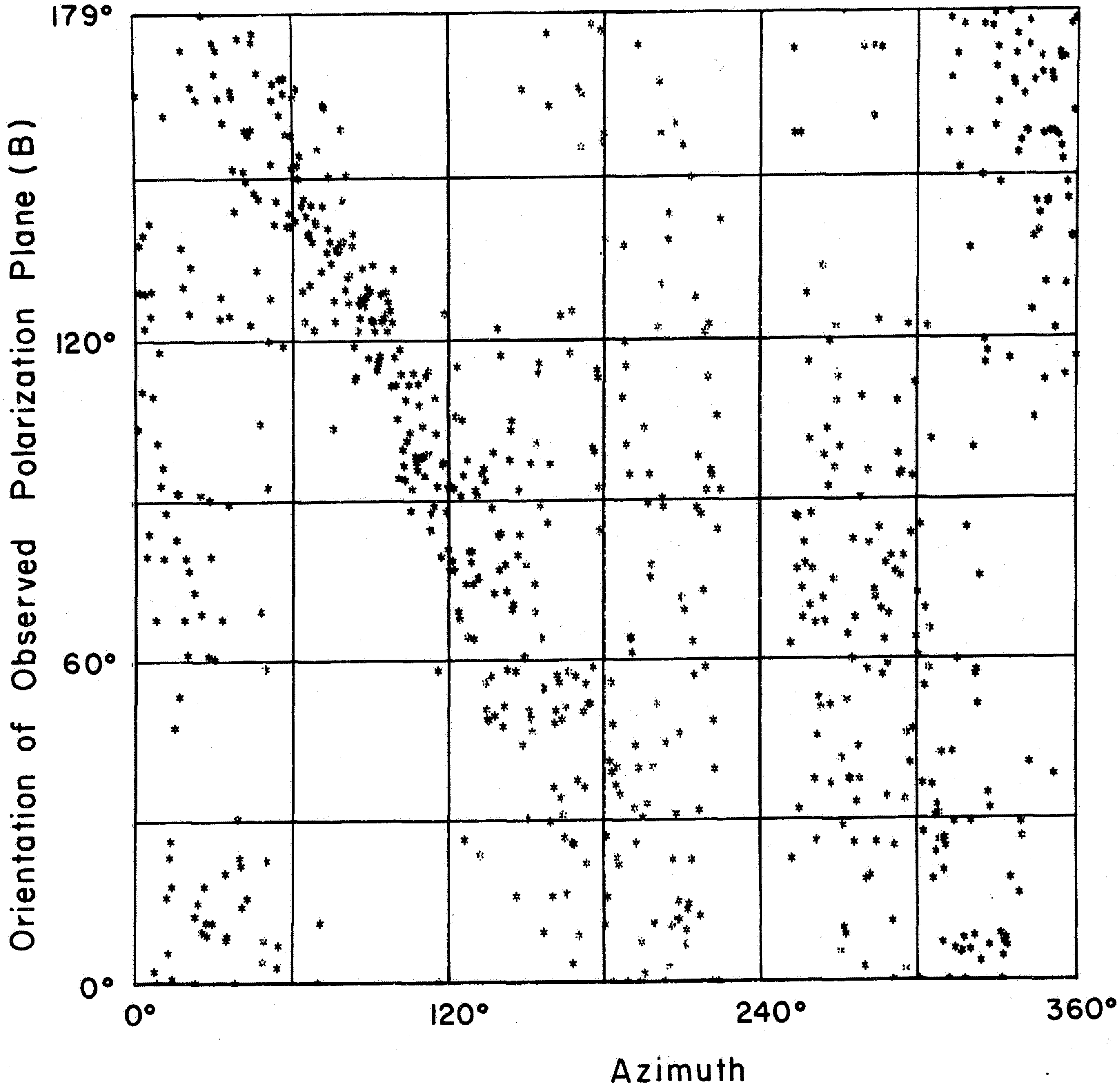

179°
120°
60°
0°
Orientation of Observed Polarization Plane (B)
0°
120°
240°
360°
Azimuth

Fig. 7